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# Micro-Scale Avionics Thermal Management

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## Abstract

Trends in the thermal management of avionics and commercial ground-based microelectronics are converging, and facing the same dilemma: a shortfall in technology to meet near-term maximum junction temperature and package power projections. Micro-scale devices hold the key to significant advances in thermal management, particularly micro-refrigerators/coolers that can drive cooling temperatures below ambient. A microelectromechanical system (MEMS) Stirling cooler is currently under development at the NASA Glenn Research Center to meet this challenge with predicted efficiencies that are an order of magnitude better than current and future thermoelectric coolers.

## Introduction

The critical need for advanced thermal management technologies is well recognized in the semiconductor industry. In fact, according to Intel's Chief Technology Officer Pat Gelsinger, heat is becoming one of the most critical issues in computer and semiconductor design [1]. The most recent edition of The International Technology Roadmap for Semiconductors (ITRS) predicts [2]:

"... the thermal management challenge will significantly increase in the future due to increasing power, decreasing junction temperatures, and a continuing need to have cost-effective solutions."

Examination of key projections extracted from the ITRS data, and plotted in Fig. 1, demonstrates how decreasing junction temperatures and increasing power are combining to accelerate the thermal management challenge. According to these projections, there are no known solutions for reaching the reduced junction temperature predicted for 2002 and beyond for *both* high-performance and cost-performance (i.e. desktop) systems. Single-chip package power reaches this same technology void a few years later in 2005 for high-performance systems, and somewhere between 2005 and 2008 for cost-performance systems. Clearly the need exists for advanced thermal management technologies development that will meet the junction temperature and power dissipation requirements looming on the horizon.
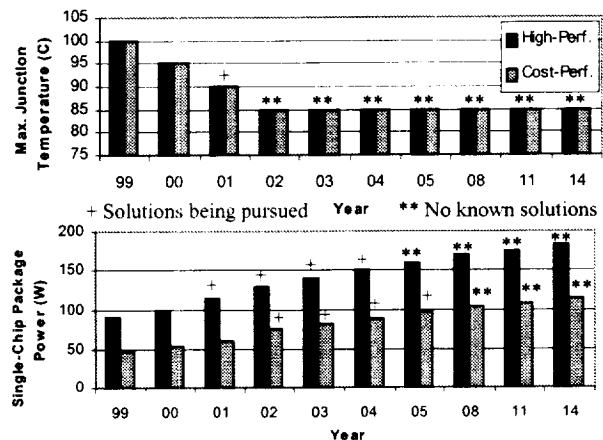


**Fig. 1: Projections for package power and allowable junction temperature illustrate thermal management technology void beginning in 2002.**

### Convergence of Thermal Management

Thermal management of electronics in aerospace vehicles (i.e. avionics) is driven by two unique environmental factors: limited or no air cooling and low gravity. Limited or no air cooling results from either high altitude operation where the air density and corresponding cooling capacity is reduced; or the vacuum of space where all heat must ultimately be dissipated by thermal radiation. Low gravity conditions, encountered in low-earth orbit and beyond, results in negligible buoyancy forces and the subsequent practical absence of natural convection. Historically, these unique environmental drivers have

tended to split the development paths of avionics cooling systems relative to commercial ground-based electronics systems where natural and forced convection air cooling have been routinely employed.

More recent drivers in the commercial electronics market, however, are causing these previously disparate development paths to converge in many respects. For example, acoustic noise concerns in commercial electronic systems are limiting the use of fan cooling; as is the trend toward portable devices such as notebook computers, personal digital assistants, cell phones, and the like. These portable systems are both volume and power constrained, and therefore often incompatible with fan cooling requirements. In some cases even bread-and-butter cooling devices such as finned heat sinks are unusable due to the lack of sufficient volume to maintain effective natural convection circulation. Consequently, heat pipes and conduction methods routinely used in avionics are becoming more common in commercial systems.

Other key drivers – increased heat flux, reduced volumes, and lower junction temperatures – are equally prevalent in both avionics and commercial electronics. As a result, thermal management techniques developed in the aerospace arena are becoming increasingly relevant to consumer electronics, and visa-versa. In both realms, thermal management systems are moving beyond "fins & fans" into cooling solutions that are performance optimized for a particular application; and in some cases integrated into the electronics itself – often at the chip package level. The pervasive trend of continued miniaturization, which has been driving the microelectronic industry for decades, is also shared by both avionics and commercial systems.

Avionics and commercial ground-based electronics systems still differ of course in terms of their economic drivers. In general the primary driver for avionics is performance; whereas, price drives commercial systems. However, the use of commercial off-the-shelf ("COTS") components in avionic systems is a major thrust in recent years reflecting the growing emphasis of price (and availability) in aerospace applications. Similarly, although targeting a price point based on market forces is the key economic driver for commercial electronics, performance provides critical product differentiation in an ever increasingly competitive marketplace. Therefore, even in terms of economic drivers, avionics and commercial ground-based electronic systems have far more in common now than in years past.

## The Thermal Management Toolbox

Thermal management techniques can be conveniently grouped into passive and active. Passive methods, which do not require any input power, tend to be very reliable and relatively easy to implement. However, they are also performance limited and therefore inadequate for many high-power applications. Passive methods include:
- Natural convection (finned heat sinks, ventilation slots, board/component placement, etc.)
- Radiation (paints, coatings, mechanical surface treatments, component layout, etc.)
- Conduction (structures, vias, elastomers, pastes, adhesives, pads, chip packages, etc.)

Strictly speaking, capillary and phase change methods (e.g. heat pipes, wicks, melting wax, boiling, etc.) are also passive methods. However, they generally provide higher performance capabilities and are not as easily implemented as the other passive methods. In addition, phase change devices are limited in terms of their operating temperatures, which are determined by the saturation temperature of the working fluid (or melting temperature of the solid).

Active thermal management techniques – those that require input power – provide increased performance/capacity, but generally at the price of lower reliability and added complexity. Active methods include:
- External forced convection (fans, nozzles, etc.)
- Pumped loops (heat exchangers, cold plates, etc.)
- Refrigerators & coolers (thermoelectric/Peltier, vapor-compression, vortex, gas cycles, etc.)

It should be noted that heating (e.g. resistance, induction, etc.) is also an active thermal management tool for applications where a lower temperature boundary must be avoided. Aerospace applications requiring heating are common due to the effective thermal radiation sink temperature of space being a few degrees above absolute zero. On earth, cold region applications may also require heating. In addition, measurement electronics or other systems where a fixed temperature band must be maintained often require an integrated cooling and heating system with temperature feedback control.

### Micro-Scale Thermal Management
While the traditional thermal management techniques described above have provided system-level cooling sufficient to meet past electronics cooling requirements, they are unable to meet future requirements in their current form as evidenced by the ITRS projections [2]. Miniaturization of thermal management techniques to the micro-scale, which has

lagged the semiconductor industry's advances in microelectronics, is receiving increased attention as a solution to the future thermal management technology shortfall. Micro-scale thermal management offers several enticing opportunities:

1. Ability to "spot cool" high heat flux regions with unparalleled resolution to bring down critical junction temperatures.
2. Potential for macro-level performance leaps by optimizing micro-level heat transfer.
3. Improved integration of thermal management at the chip level using compatible semiconductor materials and fabrication techniques.
4. Enabling of system-level miniaturization to support the pervasive trend toward increased capabilities in smaller devices.

In addition to increased heat flux for traditional scale avionics, the aerospace industry's interest in micro-scale thermal management is being driven in part by NASA's plans to develop micro-satellites/spacecraft, and embedded miniature sensors and actuators [3]. Likewise, the commercial electronics adoption of microsystems is evidenced by a recent market study predicting an increase in MEMS use in consumer electronics from $200 million in 2000 to more than $1.5 billion in 2005, *excluding* inkjet print heads and hard disk drives [4]. Applications include camcorders, digital cameras, cell phones, optical drives, laptops, portable CDs and DVDs, game controllers, MP3 players, PDAs/Pocket PCs, and digital projection TVs. Currently found in less than 0.1% of these consumer electronics products, MEMS devices are expected to be found in nearly 5% by 2004; and will take until 2006 to approach 10%.

### Recent Developments & Ongoing Research

There is a wide range of new technology developments in micro-scale thermal management; a complete overview of the topic is well beyond the scope of this paper. However, brief discussion of a few relevant examples sheds some light on the promise the field holds for cooling microelectronics.

A good deal of work has been done relative to microchannels that provide increased surface area for improved heat transfer. These devices are generally limited to laminar flow regimes since the increased surface area also increases pressure drop and the subsequent pumping power required. The channels can be micromachined from bulk semiconductor material, or fabricated by other means with a variety of materials. "Microtubes", for example, have been developed by Edwards Air Force Base using copper, silver, platinum, glasses, polymers, alloys, and other materials with diameters ranging from 0.5 to 410 microns [5].

Development of micro-scale wicking structures utilizes surface tension forces of the working fluid to induce flow without active pumping. Used in conjunction with evaporator and condenser regions, these wicking structures become a critical component of micro-heat pipes. NASA Glenn Research Center has funded work in this area by the University of Cincinnati that has fabricated a working wick structure with a coherent pattern of 2.5 micron diameter pores (channels) 260 microns in length [6]. The wick is part of a micromachined silicon loop heat pipe concept for removing heat at the chip level with a predicted heat flux cooling capacity greater than 100 W/cm².

Improved materials offer enhanced micro-scale thermal conduction. Diamond films have long been a material of particular interest in high performance electronics cooling due to their unusual combination of superior thermal conductivity (~2000 W/m-°K) yet low electrical conductivity. Argonne National Laboratory has developed a nanocrystalline diamond film from fullerenes resulting in free-standing diamond structures as thin as 0.3 microns [7]. Another example is the emerging developments in carbon nanotubes that offer the potential for ultra-high strength structures with outstanding thermal conduction characteristics (e.g. >5000W/m-°K).

### Micro-Refrigerators/Coolers

Micro-refrigerators and coolers have a unique characteristic for chip-level cooling that differentiates them from all other potential thermal management technologies: *the ability to generate cooling temperatures well below the ambient temperature.* This key advantage potentially allows junction temperatures to be driven much lower resulting in improved reliability, faster performance, and operation in higher temperature environments. Note that each 10°C drop in transistor temperature results in a 1-3% increase in semiconductor switching time [8].

Thermoelectric or Peltier coolers are the most common refrigeration devices used for electronics cooling, and have been scaled to the micro-domain. Unfortunately thermoelectrics have very low efficiencies resulting in high power requirements and added waste heat. At a no-load cooling temperature of 0°C and a rejection temperature of 25°C, current thermoelectric technology has a coefficient of performance (COP; the ratio of cooling capacity to input power) of approximately 0.3; and predicted to improve to only 0.4 in the next decade [9].

Much higher efficiencies are possible with the Stirling refrigeration cycle. For the same conditions described above, current Stirling coolers

have a COP on the order of 5.0, or roughly an order of magnitude increase in efficiency relative to thermoelectrics. However, attempts to miniaturize such a device for application in electronics cooling have been size-limited by the use of traditional components (e.g. pistons, linkages, and pressure vessels) and traditional fabrication methods [10,11].

As a result, Stirling coolers have been impractical for most electronic packaging applications. The only attempt known by the author to approach the micro-scale is documented in a series of cryocooler patents that use diaphragms instead of pistons to drive the working gas[12].

## MEMS Stirling Cooler

A device for bringing the inherent high efficiency and cooling capacity of the Stirling refrigeration cycle to the micro-domain is under development at the NASA Glenn Research Center, and merges two core capabilities at the Center: Stirling machines and microsystems. NASA Glenn has been developing Stirling machines for power generation and cooling for decades; and more recently has developed microsystems capabilities initially focused on harsh environments using silicon carbide, and is now expanding to other areas.

Figure 2 illustrates how an ideal Stirling cycle for refrigeration is produced using a traditional piston-bore geometry and a regenerative heat exchanger; along with the corresponding pressure-volume and temperature-entropy diagrams.
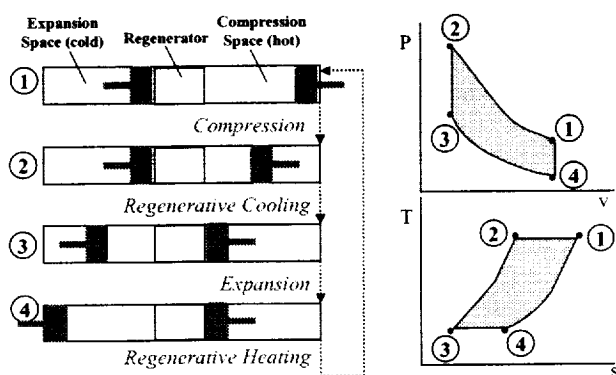


**Fig. 2: The Stirling refrigeration cycle creates a cold (expansion) region and a hot (compression) region.**

The ideal cycle starts with compression of the working gas from state 1 to 2 in an ideally isothermal process that increases the pressure and decreases the gas volume. The gas is then cooled in a constant volume process as it is forced through the regenerator into the expansion space (state 2 to 3). From state 3 to 4, the working gas is expanded in an

isothermal process that decreases the pressure and increases the gas volume. The cycle returns to its original state (state 4 to 1) with the heating of the gas in a constant volume process as it is forced back to the compression space through the regenerator.

During steady state operation, this cycle produces a cold region in the expansion space for cooling/refrigeration and a hot region in the compression space for heat dissipation. The regenerative heat exchanger functions as thermal capacitor transferring heat to and from the working gas as it is forced between the expansion and compression spaces by the pistons.

### Device Description

The MEMS Stirling cooler uses diaphragms instead of pistons to produce a Stirling refrigeration cycle, and is fabricated with semiconductor processing techniques to produce a device with planar geometry. The result is a flat cold surface for extracting heat and an opposing flat hot surface for thermal dissipation. Figure 3 shows a partial crossectional sketch of one Stirling cycle "cell". A typical device would be composed of numerous such cells arranged in parallel and/or in series, with all layers joined at the periphery of the device to hermetically seal the working gas.
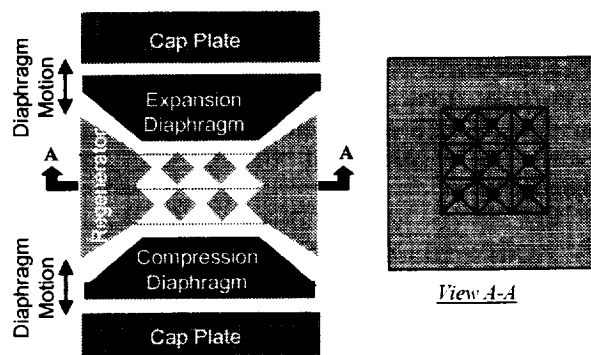


**Fig. 3: Crossectional sketch of one "cell" of the MEMS Stirling cooler illustrates the key components of the device.**

The expansion and compression diaphragms are the only moving parts, and are deflected toward and away from the regenerator region in phase-shifted sinusoidal fashion to produce the Stirling refrigeration cycle. Expansion of the working gas directly beneath the expansion diaphragm in each cycle creates a cold (top) end for extracting heat; while compression at the other (bottom) end creates a hot region for dissipating heat.

Heat is transferred to and from the working gas as it is forced through the regenerator region by the moving diaphragms. The slanted geometries of

the diaphragm and regenerator surfaces are characteristic of the wet etching process used to create the structure, and advantageously increase the potential swept volume in the expansion and compression regions. The regenerator can alternatively be made up of constant crossection passages that are created after the regenerator layers are bonded.

A thin film temperature sensor deposited on the surface of the cap plate (not shown) provides control feedback. This sensor, along with the ability to switch hot and cold ends by altering the cycle with control software, permits the device to be used for precise thermal control as well as cooling.

Unique characteristics of the device include: scalability, modularity, simplified interfaces, robust design, and minimal vibration. The ability to fabricate the device at the microsystem level brings precise temperature control and cooling capabilities to a rapidly expanding variety of micro-scale devices. Modular design allows for operation of identical devices in parallel to increase capacity, or staging of identical devices by stacking in series to obtain lower temperature ranges. Electrical power alone is required for operation; and structurally-deflected diaphragms are the sole moving parts of the device resulting in limited failure modes. Induced vibration is minimized by the low inertial forces produced by the diaphragms, and can be potentially eliminated by the use of multiple devices operating out-of-phase with each other.

The MEMS Stirling cooler advances thermal management capabilities for microelectronics in four key areas:

1. Extended environmental temperature ranges
2. Precision spatial and temporal thermal control for temperature sensitive devices
3. Lowered operating temperature for increased reliability and performance
4. Enabling of micro-scale devices that require active cooling and/or temperature control
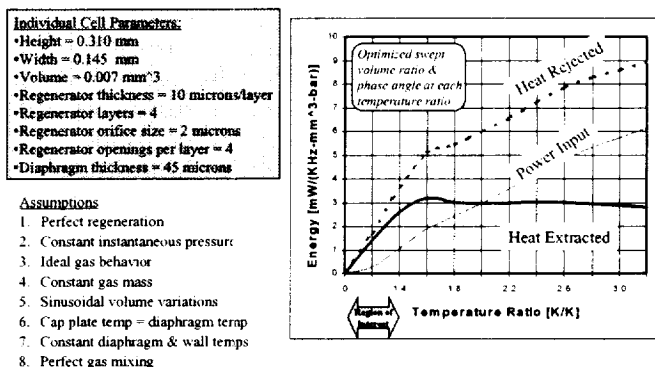
*Theoretical Performance*

The results of a first-order analysis of the device [13] are shown in Fig. 4. Based on the design parameters and assumptions shown, energy (per cycle frequency, unit device volume, and initial working gas pressure) is plotted as a function of the temperature ratio between the hot and cold ends. Using this performance plot, the heat extracted and dissipated for a given power input and temperature differential can be estimated for an application of interest.

For example, assume the case temperature of a chip package is to be maintained at 20°C (293°K). Approximately 6 cm$^3$ (less than one-inch

square by 3/8-inch thick) of volume is available on the top surface of the chip to mount the MEMS cooler. If the warm upper end of the cooler is set at 80°C (353°K) to dissipate heat to the ambient air, then the absolute temperature ratio is 1.2. Assuming the MEMS cooler has an initial working gas pressure of 20 bars and operates at 1KHz, Fig. 2 yields the following theoretical performance estimates:

» Heat extracted = 168 W
» Heat rejected = 204 W
» Power input = 36 W



**Individual Cell Parameters:**
•Height = 0.310 mm
•Width = 0.145 mm
•Volume = 0.007 mm^3
•Regenerator thickness = 10 microns/layer
•Regenerator layers = 4
•Regenerator orifice size = 2 microns
•Regenerator openings per layer = 4
•Diaphragm thickness = 45 microns

Assumptions
1. Perfect regeneration
2. Constant instantaneous pressure
3. Ideal gas behavior
4. Constant gas mass
5. Sinusoidal volume variations
6. Cap plate temp = diaphragm temp
7. Constant diaphragm & wall temps
8. Perfect gas mixing

**Fig. 4: Performance plot based on a first-order analysis of the MEMS Stirling cooler provides an estimate of the theoretical performance for chosen operating conditions.**

In the previous example, the 204 W must be rejected from the hot surface of the MEMS Stirling cooler (e.g. by conduction to the metal chassis of the device) in order to supply the 168 W of cooling at the cold surface. That is, the overall cooling system must be balanced and properly designed from chip package to heat sink in order to realize the theoretical cooling capacity indicated. However, the key feature of the MEMS Stirling cooler is the ability to drive the cold surface below ambient resulting in cooler junction temperatures; while driving the hot end to high temperatures (compared to a passive device) resulting in higher driving temperature differentials, and higher subsequent heat dissipation efficiency.

*Development Approach & Challenges*

The initial concept and analysis for the MEMS Stirling cooler was created in-house at NASA Glenn, and a patent application has been submitted based on the technology. The next phase of development is focused on building a working model by teaming with key partners possessing the critical capabilities needed.

Several primary challenges must be addressed with the working model prior to optimizing a prototype design. First, the diaphragm actuation technique must be developed and demonstrated to

produce the required force to compress, expand, and transfer the working gas. Second, details of the control electronics to drive the diaphragms and related electrical connections must be defined and tested.

A third area requiring attention is the regenerator design. The regenerator must be thermally conductive in the direction perpendicular to the flow passages to permit effective heat transfer to and from the working gas. At the same time, the regenerator must be thermally isolating in the (axial) direction parallel to the passages in order to maintain the required temperature differential between the expansion and compression regions, and minimize performance losses due to axial conduction. The layered construction of the regenerator is compatible with these requirements, allowing insulating coating materials (e.g. silicon dioxide) between layers and potential removal of bulk silicon by selective wet etching to increase the axial regenerator thermal resistance in the axial direction.

The interface between the cap plate and diaphragm layers is a fourth area of concern. Structural design and operation of the device must maximize heat transfer from the expansion and compression spaces to their respective cap plates. In addition, gas film damping between the diaphragms and cap plate must be addressed.

Finally, packaging of the working model – a crucial issue in general for MEMS devices – will require hermetic sealing of the pressurized working gas. For the working model, this may be limited to low pressure air. However, in an optimized prototype, the working pressure will be maximized since the device performance is directly (linearly) proportional to this parameter. The prototype may also utilize helium or hydrogen as a working gas, which may necessitate the use of diffusion mitigating coatings such as nitride.

**Concluding Remarks**

Micro-scale thermal management devices hold promise for meeting the upcoming technology void in avionics and commercial electronics cooling technologies. Current and ongoing research in microchannels/tubes, micro-heat pipes, high conductivity micro/nano materials, and micro-refrigerators offer the potential for significant leaps in thermal management performance relative to existing technologies routinely used in practice.

One such technology under development at the NASA Glenn Research Center, a MEMS Stirling cooler, will permit below-ambient cooling and temperature control at efficiencies that are an order of magnitude improvement over current and future thermoelectric coolers. This technology has notable implications for microelectronic thermal management including the enabling of further system-level miniaturization. Furthermore, advances in this technology may lead to related developments of MEMS power converters that operate on the Stirling cycle to convert heat (e.g. dissipated from microelectronic components) into electrical power.

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